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Arrays with Local Centers of Symmetry in Space Groups $Pca2_1$ and $Pna2_1$

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Abstract

Of the several hundred structures in the Cambridge Structural Database [version 4.6 (1992), Cambridge Crystallographic Data Centre, 12 Union Road, Cambridge, England] having space groups $Pca2_1$ or $Pna2_1$ and more than one molecule in the asymmetric unit ($Z > 4$), approximately three-quarters contain local centers of symmetry. These local centers, which are not crystallographic centers, occur predominantly near $x = \frac{1}{8}$, $y = \frac{1}{4}$ in $Pca2_1$ or near $x = \frac{1}{8}$, $y = 0$ in $Pna2_1$; this also holds for the limited number of examples we have examined of pseudo-centrosymmetric molecules with $Z = 4$. Local centers at these points create unusual correlations between corresponding atoms in the two molecules.

1. Introduction

It has been recognized for over 50 years, probably first by Nowacki (1942), that the symmetry elements most favored in the structures of molecular crystals are twofold screw axes, glide planes, and inversion centers. Indeed, in a recent comprehensive review of space-group frequencies and their relevance, '*Towards [the Construction of] a Grammar of Crystal Packing*' Brock & Dunitz (1994)‡ found that, of 31 770 'reliable' structures reported in the July 1991 issue of the Cambridge Structural Database (1992; CSD), over 38% belong to a single space group, $P2_1/c$, one of the two space groups (*Pbca* is the other) that contain these three types of symmetry elements and no others. The six space groups $P2_1/c$, $P\bar{1}$, $P2_12_12_1$, $C2/c$, $P2_1$ and *Pbca* accounted for over 85% of the entries; of these, only $C2/c$ contains any symmetry element other than these three (an additional twofold axis). Brock & Dunitz (1994) also note that 'Inversion centers are favorable'; of the approximately 25 000 achiral structures, over 95% contain inversion centers. For chiral structures, where glide planes and inversion centers are prohibited, the overwhelmingly favorite space groups are the two that contain 2_1 axes only: $P2_12_12_1$ (55%) and $P2_1$ (30%).

Notable exceptions to the general rule that achiral structures contain inversion centers are two space groups within the orthorhombic point group C_{2v}, $Pca2_1$ and $Pna2_1$, which together account for over 700 entries. (These are the only space groups to contain 2_1 axes, glide planes, and no other symmetry element.) Over the years we have noticed that many structures in these two space groups contain closely centrosymmetric arrays, comprising either individual, approximately centrosymmetric molecules (one per asymmetric unit) or a centrosymmetric pairing of two crystallographically independent molecules (which are generally without symmetry); we have also noticed that the additional (local) centers of symmetry tend to lie as far as possible from the other symmetry elements of the space groups. Somewhat similar observations were made by Ermer & Röbke [1994; footnote (7)] for space group $Pna2_1$; among the 1834 examples (from the 1994 issue of the CSD) in this space group that they examined, they identified 11 'virtually centrosymmetric molecular structures' (*i.e.* $Z = 4$) and 35 'almost ideally centrosymmetric, weakly bound dimers' (*i.e.* $Z = 8$).

More recently, our attention returned to this topic when we examined the crystal structure of 2-benzyloxy-6-methoxybenzaldehyde, $C_{15}H_{14}O_3$, (Lemercier *et al.*, 1994; $Pca2_1$, $Z = 8$). The two molecules in the asymmetric unit are closely related by a non-crystallographic center of symmetry; we also noted that there were surprisingly large disparities between pairs of corresponding bond lengths in the two molecules, suggesting that there might be unusual correlations resulting from the additional local center. These observations encouraged us to make a more thorough survey of the situation. We have confirmed that additional, non-crystallographic centers tend to lie at preferred positions in these two space groups, and we have also found that these additional local centers do indeed give rise to predictable and potentially serious correlation terms between related pairs of atoms, leading to increased uncertainties in the differences between corresponding bond lengths and angles.

We note two recent papers. The first, '*Symmetry, pseudosymmetry and hypersymmetry of organic crystals*' (Zorky, 1996), has some overlap in terms of ideas with the present paper although the space groups $Pca2_1$ and

† Deceased.

‡ Tables 1 and 5 and footnote 57 of this paper are particularly relevant in the present context.

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Pna2_1 are not specifically mentioned. The second is entitled '*Distribution of Molecular Centres in Crystallographic Unit Cells*' (Motherwell, 1997); 'centre' here is defined as 'the mean value of the *x*,*y*,*z* fractional coordinates for all reported atoms, including H if present'. This is quite different from our usage as a (local) center of *symmetry* and there is no overlap with the present paper.

2. Experimental

Our survey is based primarily on the October 1997 release of the CSD. From it, we have extracted and examined all structures in space groups No. 29 (*Pca*2_1) and No. 33 (*Pna*2_1) having more than one molecule per asymmetric unit, that is, with $Z > 4$ (Z must also be divisible by 4, since neither of these space groups contains any possible molecular symmetry element). After eliminating those with incomplete or questionable atomic coordinates, we obtained a list of 247 valid unduplicated entries for *Pca*2_1 and 205 for *Pna*2_1. For each of these entries we searched the list of coordinates looking for local centers of symmetry using a program devised by one of us (VS). We found such local centers for 169 structures in *Pca*2_1, to which must be added three for $Z = 4$. In *Pna*2_1 there were 156 structures with local centers for $Z > 4$, and 13 with $Z = 4$. Thus, approximately 70 and 82% of the total samples have local centers in the two space groups. (There are four examples in *Pca*2_1 and three in *Pna*2_1 where two distinct centers could be identified, relating different pairs of molecules.) The compounds showing local centers and the coordinates of these centers are listed in Table 1 (*Pca*2_1) and Table 2 (*Pna*2_1), of the Supplementary Material.† They are identified by their CSD REFCODES and the 35 examples ($Z = 8$) of Ermer & Röbke (1994) are included. A few examples having $Z = 4$ (that is, where the local center is contained within the single molecule in the asymmetric unit) which we happened across are also included in Table 1 and Table 2, as well as the 11 *Pna*2_1 examples of this type given by Ermer & Röbke (1994). There are undoubtedly many more examples of approximately centrosymmetric molecules with $Z = 4$ but we have not attempted to search for them.

A number of comments are in order. First, since both of these space groups are polar, with an unidentified origin along the [001] direction, we have in all cases placed the local center at $z = 0$ (in two of the examples of structures with two distinct local centers, the two centers differ by 0.25 in z). Second, we emphasize that these are *local* centers of symmetry, which relate certain pairs of molecules (or half-molecules) but not others; the total structures are *not* centrosymmetric. There are four of these local centers within a unit cell, related by the operations of the space group; for them to be true crystallographic centers, eight would be needed. Third, we have in most cases either referred the coordinates in the CSD to an alternative origin (in the *ab* plane), or transformed the local symmetry center by one of the space-group operations, or both, in order to place the center within the region $0 \le x \le 0.25$, $0 \le y \le 0.25$ for uniformity. Fourth, the quality of fit to the local centers shows a large variation among the various compounds. These local centers are obeyed almost within the experimental errors for, say, GAPWAV and NIPALA in *Pca*2_1 and for JIRDOD and JOFHIV in *Pna*2_1; in other cases, the r.m.s. mismatch is 0.3 Å or more. An extreme example is GAFHAW in *Pna*2_1, where the r.m.s. mismatch of the z coordinates is nearly 1 Å; this compound is on (or, perhaps, beyond) the borderline of relevant examples.

3. Location of the extra local centers and possible consequences

In Figs. 1 and 2 we show plots of the positions, in the *ab* plane, of the local centers of symmetry for the two space groups. As these plots clearly indicate, in each space group there is a highly preferred position for the center: at about $x = \frac{1}{8}$, $y = \frac{1}{4}$ for *Pca*2_1 and at about $x = \frac{1}{8}$, $y = 0$ for *Pna*2_1. These preferred positions are, indeed, well separated from the true symmetry elements of the two space groups, although there is also a small cluster in *Pna*2_1 around the point $x = \frac{1}{8}$, $y = \frac{1}{4}$, which lies on the *a*-glide plane.

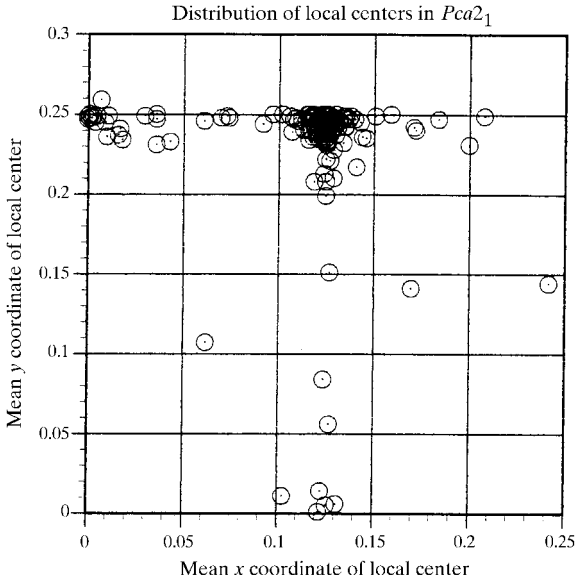

Fig. 1. Paired scatter plot of the distribution in x and y of the coordinates of the local centers in space group *Pca*2_1 (176 data points from Table 1 of the Supplementary Material).

† Supplementary data for this paper are available from the IUCr electronic archives (Reference: BK0058). Services for accessing these data are described at the back of the journal.

The local centers tend to avoid the special positions $x = 0$ or 0.25, $y = 0$ or 0.25 where, if exact centers were to occur, the space group would automatically be changed to one of symmetry D_{2h}, and the entire structure would become centrosymmetric. In this regard, we note a small cluster of examples where the local center in space group $Pca2_1$ lies close to $x = 0$, $y = \frac{1}{4}$, suggesting that these structures should properly be described in the popular space group *Pbca*. We have examined these structures as closely as the available data permit, and in most cases find that deviations from the local center (as indicated by the square root of the mean-square deviation of the individual atoms from the local center, given as r.m.s.d. in Tables 1 and 2) are large enough, and features of the structure convincing enough, to suggest that no true center is present and that the structure as reported is correct. However, further investigation is required to establish whether the compounds CIJVAS, DIXVOV, FECTOW, FOWYUL10, YIMBUR, YUGRUN, ZUFWIG and ZUXXAT are better described in *Pbca* than in $Pca2_1$.

In the case of $Pna2_1$, we note one example with a local center very close to the point $x = 0$, $y = 0.25$ that could require revision of the space group to *Pnab* (a non-standard setting of *Pbcn*). This entry is JISVEM, 1,8-diaminonaphthalene (Llamas-Saiz *et al.*, 1991; Basaran *et al.*, 1993). In this case, the two molecules related by the local center are appreciably non-parallel, due to a pyramidal hydrogen-bond arrangement, and the local center is a relatively poor one; there is no reason to doubt that the space group is indeed $Pna2_1$. A particularly interesting example is AMBACO, anthranilic acid (*o*-aminobenzoic acid), with a very good local center near the point $x = \frac{1}{4}$, $y = 0$ that would generate space group *Pnaa* (a non-standard setting of *Pccn*). Both X-ray (Brown, 1968) and neutron (Brown & Ehrenberg, 1985) diffraction studies have shown that the structure contains two tautomeric forms of the molecule, one neutral (protonated at the carboxyl group) and one zwitterionic (protonated at the amino group), and hence that the additional symmetry cannot be exact. This structure has been refined (correctly) in a non-centrosymmetric space group, but nevertheless is nearly centrosymmetric. Much previous experience shows that refinement (incorrectly) of a centrosymmetric structure in a non-centrosymmetric space group leads to distortions in bond lengths, and the question arises whether a similar effect may not occur in AMBACO. The availability of both X-ray and neutron measurements makes the situation even more intriguing, but we have not explored it further. We note that there are two other polymorphs of anthranilic acid, both with one neutral molecule in the asymmetric unit; phase relationships in the system have been re-investigated (Ojala & Etter, 1992).

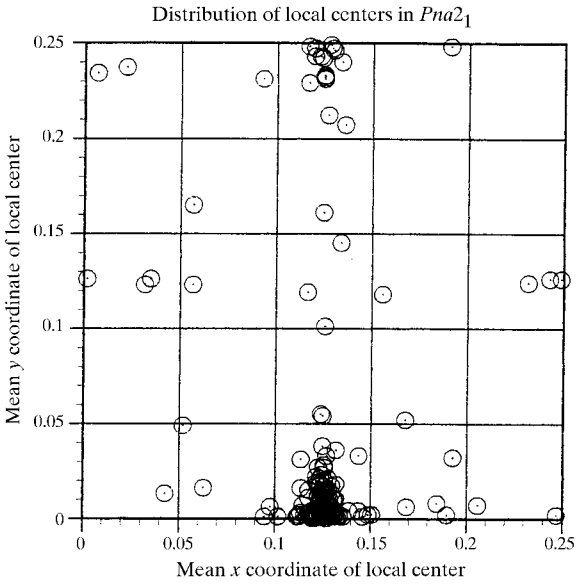

Fig. 2. Paired scatter plot of the distribution in x and y of the coordinates of the local centers in space group $Pna2_1$ (171 data points from Table 2 of the Supplementary Material).

4. Correlations due to hypersymmetry

Hypersymmetry of any sort leads to correlations between the coordinates of related atoms: if one thinks in terms of a Patterson function, whenever two interatomic vectors are superposed, they cannot be distinguished and correlation must result. In most cases, however, the preponderance of non-superposed vectors (particularly intermolecular ones) removes most of the correlation and nearly normal refinement results can be expected. In the present examples, where the local inversion centers have such special coordinates, many of the intermolecular vectors also superpose, and correlations become much more serious – and also rather surprising.

When a structure contains a local center of symmetry near $x = \frac{1}{8}$, $y = \frac{1}{4}$ in $Pca2_1$, or near $x = \frac{1}{8}$, $y = 0$ in $Pna2_1$, some large correlations and rather peculiar refinement results can be anticipated. In the first place, for reflections with $h = 2n$, corresponding atoms in the centrosymmetrically related pairs will be completely correlated; for these reflections, the local center becomes a global center. The reflections with h odd show, in general, no unusual correlations, either positive or negative; they do not offset the effect of the h even reflections, but merely reduce it. One can expect, then, that on average (and excluding any other special features of the structure, such as the polar c axis which introduces its own correlation problems), corresponding atoms in the two molecules would show correlation coefficients of approximately 0.5 between all three pairs of coordinates. However, if in addition to the local centers involving the entire structure, some of the atoms have special values for their y coordinates (0.0 and 0.5

for a pair of related atoms in space group $Pca2_1$, 0.25 and 0.75 in $Pna2_1$) even more severe problems arise. In the first place, these atom pairs do not contribute to reflections with h odd (this is a characteristic of the space group, not of the additional local center). Moreover, for these h odd reflections the derivatives with respect to the x and z coordinates vanish; as a result, the singularities created by the h even reflections remain uncompensated and standard refinement of the x and z coordinates for these atoms is impossible. On the other hand, the derivatives with respect to y are large for these h odd reflections while they vanish for the h even reflections, and the singularity in the y coordinates is removed. In other words, for these special values of y, coupled with the special values of the coordinates of the local centers of symmetry, the x and z coordinates cannot be refined by normal least-squares methods (using first derivatives only) while the y values will refine normally. (In this discussion we presume that equivalent atoms have identical, isotropic displacement parameters. These also show unusual correlations.)

2-Benzyloxy-6-methoxybenzaldehyde (Lemercier *et al.*, 1994) can serve as an example. There is a nearly exact local center at $x = 0.125$, $y = 0.239$, and seven of the 18 pairs of heavy atoms have y coordinates within 0.05 parameter units of 0.0 (and 0.5). As a result, the average intensity of reflections with h odd is less than half that of reflections with h even, and correlations between pairs of x and z coordinates would be expected to be especially large. From the inverse of the full least-squares matrix of non-H atom coordinates (107 parameters, with the z coordinate of one O atom constrained), we obtained correlation coefficients between pairs of related atoms ranging from 0.22 to 0.62 for the x coordinates, from -0.05 to 0.34 for y, and from 0.51 to 0.80 for z (some of the z correlation is due to the polar axis); the largest correlations in x and z (and the smallest in y) are for pairs of atoms lying very close to $y = 0$ and $y = 0.5$.

Since the large correlation coefficients between pairs of pseudo-centrosymmetrically related atoms are positive, correlations between corresponding interatomic distances involving the pairs of atoms are negative; the difference between two such distances is known less precisely than their sum. For 2-benzyloxy-6-methoxybenzaldehyde we have evaluated the s.u.'s of the sums of and the differences between the 19 pairs of covalent bond lengths in the two pseudo-related molecules, taking into account all variances and covariances among the coordinates of the four atoms involved in each pair of bonds. (This program was also written by VS.) For all 19 pairs of distances, the s.u.'s of the differences in bond lengths were larger than those of the sums by factors ranging from 1.2 to 2.2. In other words, the expected differences to be feared between pairs of pseudo-equivalent bond lengths are appreciably larger than would be expected if the covariances had been ignored. On the other hand, *average* values of equivalent bond lengths are, as best as we can deduce, unaffected by this type of pseudo-symmetry, just as in the more drastic (and more common) case where the additional pseudo-symmetry involves global centers rather than local ones, as in AMBACO (to a good approximation).

5. Conclusions

The problem of singularity whenever an attempt is made to refine a centrosymmetric structure in a non-centrosymmetric space group is well known: meaningful parameters cannot be obtained. The problem is less severe in the present cases of local centers of symmetry, and it is unlikely that the local centers will ever be exact enough, and the coordinates of the atoms special enough, to lead to true singularities. Nevertheless, covariances will usually be important; if they are not taken into proper account, structural differences between two molecules in an asymmetric unit may appear to be significant when, in fact, they are not. While we have not investigated other space groups, we would be surprised if similar problems do not exist. We believe the moral is that whenever the presence of non-crystallographic symmetry creates a local center of inversion, extra care should be taken in evaluating the results and, in particular, to examine the interatomic covariance terms.

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